SPACE DEBRIS MITIGATION: ENABLING FUTURE ENDEAVORS

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SPACE DEBRIS MITIGATION: ENABLING FUTURE ENDEAVORS

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Space debris has become a vast and hazardous problem. It is time to acknowledge that while space may be infinite, Earth's orbital space is a finite resource that must be controlled properly. For that reason, this master's thesis will allow readers to acquire more awareness about the vast extent of human made objects flying currently all over, orbiting the Earth. At first, an explanation and more information about the history of the space debris problem will be stated, how we have been able to track the debris and why it is important. Next, current policies and organizations that were endorsed in the past will be addressed, and those that are still in use today. Followed by previous and current studies/techniques being researched on ways to reduce the amount of space debris. Lastly, a new mitigation subsystem will be introduced as a way to enable future endeavors and reduce the amount of objects in space once a satellite has reached its maximum operational capability. This thesis will also include the effectiveness of each technique. Data sources include

the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), space debris and policies studies, and other related university papers and research.

Accepted by: ________________________________, Chair
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Glossary

List of Acronyms

ADRV – Active Debris Removal Vehicle

ASAT – Anti-Satellite

CAD – Computer Aided Drawing

DOD – Department of Defense

ESA – European Space Agency

ESTEC – European Space Research and Technology Centre

GEO – Geostationary Earth Orbit

GEODSS – Ground-Based Electro-Optical Deep Space Surveillance System

IADC – Inter-Agency Space Debris Coordination Committee

ISS – International Space Station

JSC – Johnson Space Center

Km – Kilometer

LEO – Low Earth Orbit

MEO – Medium Earth Orbit

NASA – National Aeronautics and Space Administration

SLS – Space Launch System

SpaDE – Space Debris Elimination Project

SSA – Space Situational Awareness

SSN – Space Surveillance Network

STSC – Scientific and Technical Subcommittee

UN – United Nations

UNCOPUOS – United Nations Committee on the Peaceful Uses of Outer Space

USSR – Union of Soviet Socialist Republic

Chapter 1: Introduction and Context

In an effort to further explore our universe, mankind has been undertaking endeavors into space starting with the launch of Sputnik-1 in 1957. Much progress has been made in the recent decades, including manned spaceflight resulting in over 4,000 rocket launches (Garcia, Mark). Amongst all of our accomplishments, however, we have neglected to address a sleeping giant in the world of threats for space missions: space debris. The earth is surrounded by many forms of natural orbital debris such as meteoroids; however, there is also an ever-growing volume of manmade debris orbiting the earth. Space junk, space debris, or orbital debris is unwanted objects that is left orbiting around in space caused by a variety of reasons. The population of orbital debris consists of different types of objects created in numerous ways, from highly energetic disintegration of spacecraft to slow diffusion of liquid metal. This includes the non-functional spacecraft and inactive satellites that ended their missions, abandoned launch vehicle stages, mission-related debris and fragmentation debris.

Space debris is usually located in low Earth orbit (LEO) that spans from 300-2,000 km above Earth's surface. These objects stay in orbit for a long amount of time, causing their orbit to hardly be decelerated and controlled. The medium Earth orbit (MEO) is a geocentric orbit located at a distance of 2,000-35,786 km above the surface of Earth. Finally, geostationary Earth orbit (GEO) is a circular orbit located at 35,786 km above the Earth's equator that follows the direction of the Earth's rotation. Although much of the space debris is positioned in LEO, there is plenty of undesirable debris in GEO as well.

Slowly but constantly, the orbital space around Earth has started to become polluted. Ever since the first space launch, the launching of new satellites along with explosions of rockets/spacecraft to put potential satellites in orbit started the establishment of space debris.

According to Nicholas Johnson, a chief scientist working on space debris at the National Aeronautics and Space Administration (NASA), "space debris or orbital debris refers to all artificial objects in Earth's orbit that are not used for a specific purpose. NASA's preferred terminology of "orbital debris" is defined as all human objects in orbit around the Earth which have lost their value or usefulness. The debris may originate in one of three ways: mission-related operations, accidents, or international creation. Orbital debris is everywhere in orbit around Earth, and poses a serious threat to space missions of today and the future" (Garcia, Mark).

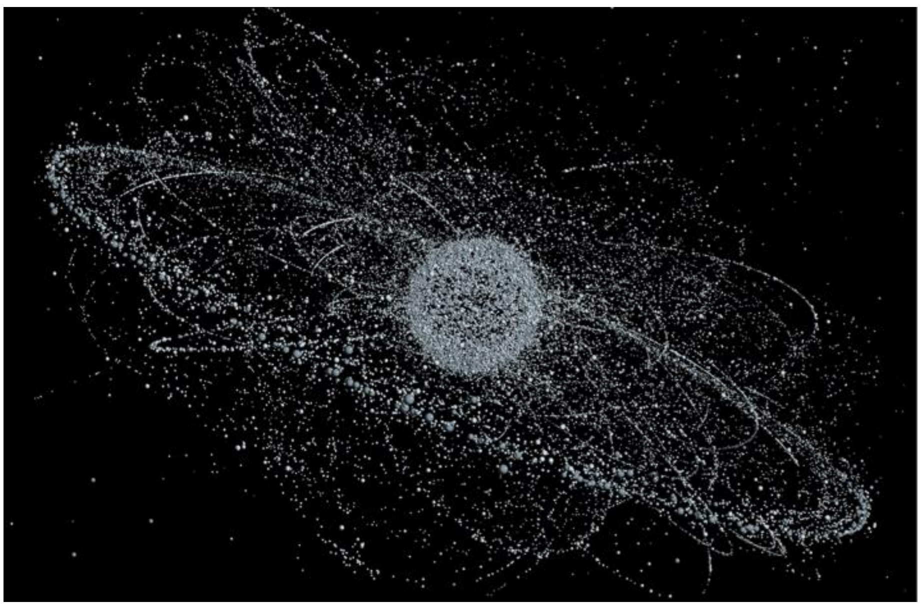

Figure 1: Orbital debris surrounding the Earth (Yuricich, Jillian)

We know that this threat of too much pollution in space exists; however, we are still unaware of when this threat will become an economical problem for space exploration, how to eliminate the current debris, and ways to prevent future debris. The economics of the situation is very complicated and still an underdeveloped field since most of the technologies proposed are experimental and estimating a cost metric is purely hypothetical. On the other hand, political measures have been taken to establish international rules to increase awareness and hopefully prevent future collisions. The most rational place to start when analyzing would be the purpose; what problem are we trying to fix?

1.1 Space Debris: The Definition, The Problem

The space industry has been around for over half a century, and the introduction of this industry was born out of conflict. Many recall the “Race for Space” in the form of the United States versus the Soviet Union. Since the launch of Sputnik-1 in 1957, space activities have created an orbital debris environment that poses increasing risks to existing space systems, including human space flight and robotic missions (Garcia, Mark). It is crucial to comprehend what is meant by debris in the context of the space environment. Before analyzing where orbital debris comes from, it would be beneficial to know what the accepted definition of orbital debris is. However, there is no universally accepted definition. The primary concern with orbital debris is that it pollutes the outer space environment by making satellites more susceptible to damage and termination or end of life from collision. Thus, as pointed out by Senechal, “everything orbiting around Earth poses some level of risk to every other object in orbit. The issue is which of those objects should be classified as orbital debris. At the outset, objects and particles that occur naturally in space, even though they do pose some risk to satellites, should be excluded from the definition of orbital debris because humans have no way to control the creation, movement, or removal of those types of objects in space” (Senechal, Thierry).

Throughout this thesis, only man-made debris will be discussed. It will not include the natural fast-moving particles known as meteoroids. It is accurate that meteoroids can also be a source of concern. Some of them can be very large with a mass of several thousand metric tons. Every day, Earth’s atmosphere is struck by millions of small meteoroids but most never reach the surface because they are vaporized by the intense heat generated when they rub against the atmosphere (Senechal, Thierry). Therefore, non-man-made debris is beyond the extent of this thesis.

In his article "Space Debris: Legal and Policy Implications," Howard Baker (Senechal, Thierry) divides space debris into three categories: inactive payloads, operational debris, and fragmentation debris. This thesis will be referring to these categories as follows:

(1) Inactive payloads or inoperative objects: Inactive payloads are primarily made up of satellites which have run out of fuel for station-keeping operations or have malfunctioned and are no longer able to maneuver. However, the use of the term "inactive payloads" requires clarification. Because satellites can be deactivated for periods of time and then later reactivated, and because debris may include objects manufactured in outer space and not just payloads, the term "inoperative objects" may be more correct when referring to objects which entities can no longer control.

(2) Operational debris: Operational debris includes any intact object or component part that was launched or released into space during normal operations. The largest single category of this type of debris is intact rocket bodies that remain in orbit after launching a satellite.

(3) Fragmentation debris: Fragmentation debris is created when a space object breaks apart. This type of debris can be created through explosions, collisions, deterioration, or any other means. Some debris has been caused intentionally.

Understanding how debris is generated could support the underlying problem due to various forms of debris. One source is discarded hardware. For instance, many upper stages from launch vehicles have been left in orbit after they are spent, which is referred to as operational debris. Many satellites are abandoned at the end of their life; we call this inoperative debris. Another source of debris is spacecraft and mission operations, such as deployments and separations. A major contributor to the orbital debris background has been object breakup. Breakups generally are caused by explosions and collisions causing fragmentation debris. For instance, the Union of Soviet Socialist Republics (USSR) has intentionally destroyed several reconnaissance satellites to prevent their recovery by other Russian States or countries. In 1985, the US also tested an air launched anti-satellite (ASAT) weapon that produced 230 pieces of trackable debris, and in 1986, intentionally caused two US satellites to collide, producing hundreds more pieces of detectable debris (Senechal, Thierry). Collisions are another source of fragmentation debris. Debris of this type may also result from collisions between space object and either natural or artificial orbital debris.

The weaponization of space has also created space debris which is still in orbit. The January 2007 Chinese destruction of a satellite has, as noted, also been a source of debris (Senechal, Thierry). The Chinese intentionally destroyed the Fengyun-1C weather satellite as a validation of the capability of a "kinetic-kill" ASAT device. Once the retired weather satellite was destroyed using the ASAT missile, a seemingly endless amount of shrapnel created a cloud of fragmentation debris around the planet. The debris cloud rose from an altitude of 200 km all the way to 3,850 kilometers, which encompasses all of LEO where most satellites operate. Chinese officials claimed that test was simply that, a test. However, the White House condemned the demonstration, and the act was universally criticized as reckless. Scientists and engineers hoped that from this, more attention to space situational awareness (SSA) research would surface in order to track debris clouds like the one the Chinese created (Yuricich, Jillian). According to Geoff Forden, within a single 100-minute orbit, an equatorial satellite passed closer than 100 km to eighteen catalogued space objects, including two functioning satellites (Senechal, Thierry). Of the sixteen pieces of debris, six are from the destroyed Chinese satellite. Fragmentation debris from this collision has been observed at altitudes as great as 3,600 km, four times as high as the original target satellite (Senechal, Thierry).

One of the biggest problems we face as a space-faring nation is determining how to reduce the amount of debris in space. There are current methods of tracking bigger debris already in space, which will be mentioned in the next section, but there are not many operational devices of preventing future debris from forming or removing current debris from space. Currently, we depend on atmospheric drag to bring down inoperative objects or orbital debris at the end-of-life cycle, which is supposed to be proved by the company at the time an object is launched.

1.2 Space Debris Management

Many space-faring nations have started to grasp the problem posed by all types of space debris and have implemented various measures to help mitigate the debris. Today, there is a wide interest in the problem from the scientific community and various incentives and organizations have been created to promote numerous guidelines and/or codes of conduct. There are several ways the United States in particular, and other nations around the world are attempting to manage the amount of debris in space.

1.2.1 Space Surveillance Network

The United States' Department of Defense (DOD) maintains a highly accurate satellite catalog on objects in Earth's orbit by a system known as the Space Surveillance Network (SSN). The SSN is the main comprehensive debris monitoring system for space debris. It has been tracking space objects since 1957 when the Soviet Union opened the space age with the launch of Sputnik-

I. The system was originally designed to detect objects of military significance, but it is capable of performing the task of monitoring many other types of space objects (Space Surveillance).

The SSN is operating ground-based radars and optical sensors at twenty-five sites worldwide. The SSN uses phased-array radars, conventional radars, and the ground-based electro-optical deep space surveillance system (GEODSS). Phased array radars can maintain tracks on multiple satellites simultaneously and scan large areas of space in a fraction of a second, and the radar energy is steered electronically. Conventional radars use immobile detection and tracking antennas. The detection antenna transmits radar energy into space in the shape of a large fan. When a satellite intersects the fan, the energy is reflected back to the antenna, triggering the tracking antenna. The tracking antenna, then, locks its narrow beam of energy on the target and follows it in order to establish orbital data. The GEODSS consists of three telescope sensors linked to a video camera. The video cameras feed their space pictures into a nearby computer which drives a display scope. The image is transposed into electrical impulses and recorded on magnetic tape. This is the same process used by video cameras. Thus, the image can be recorded and analyzed in real-time (Space Surveillance). Originally, the SSN tracked space objects which were ten centimeters in diameter or larger. Since March 2003, the sensitivity of the SSN has improved so that objects as small as five centimeters in LEO or in medium to high inclinations can now be tracked (Senechal, Thierry).

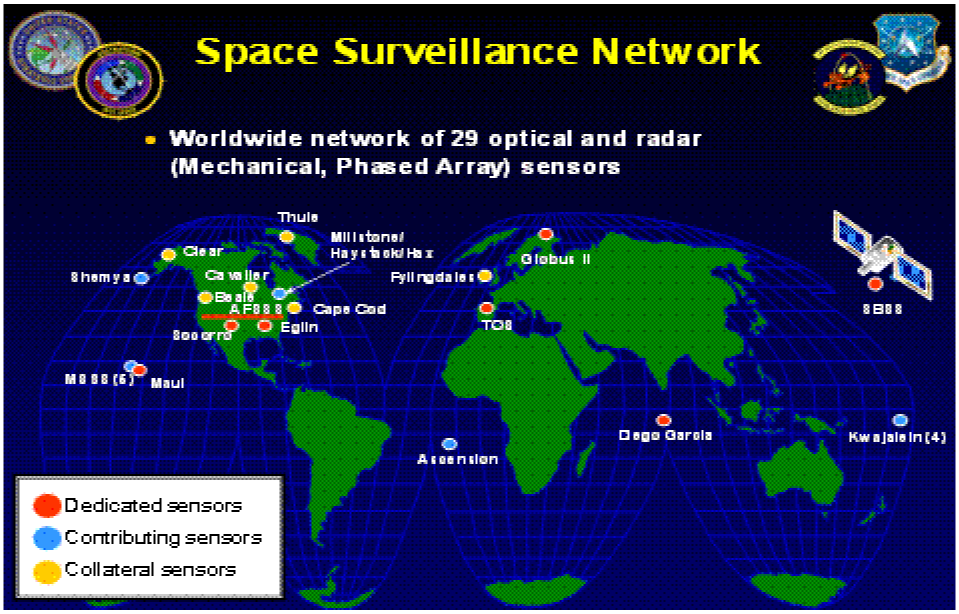

Figure 2: Space Surveillance Network Locations (Space Surveillance)

NASA and the DOD cooperate and share responsibilities for characterizing the satellite and orbital debris environment. The SSN tracks discrete objects as small as five centimeters in diameter in LEO and about one meter in GEO (Singer, Jeremy, and Colin Clark). There are more than 20,000 pieces of debris larger than a softball orbiting the Earth that travel up to speeds of 17,500 mph. There are 500,000 pieces of debris the size of a marble or larger, and many millions of pieces that are so small they cannot be tracked. Using special ground-based sensors and inspections of returned satellite surfaces, NASA statistically determines the extent of the population for objects less than ten centimeters in diameter. The greatest risk to space missions comes from the non-trackable debris, according to Johnson, a chief scientist at NASA (Garcia, Mark).

The SSN tracks about 8,000 man-made space objects orbiting the Earth. Approximately, 8% of the cataloged population is operational spacecraft, while 50% can be attributed to decommissioned satellites, spent upper stages, and mission related objects. The remainder 42% originates from on-orbit fragmentations which have been recorded since 1961 (Senechal, Thierry).

Most space debris have a mean altitude of 850 kilometers or greater. This means most of it will be long-lived (Senechal, Thierry). Most of the debris will not fall to earth for decades, and the vast majority of what does fall to Earth will burn up upon entering the Earth's upper atmosphere. The condition at some specific orbits can be described as a crowding problem. At altitudes between 700 and 1,000 km, around 1,400 km, and in GEO, this is the case. These altitudes correspond to appropriate orbits for specific missions: remote-sensing sun-synchronous missions are primarily between 700 and 1,000 km, communication satellites (and some of the main constellations) in LEO are typically above 700 and below 1,500 km, and GEO is around 36,000 km (Senechal, Thierry). Each year, new debris is created, then catalogued and tracked by various organizations. For instance, in 2006, more than 300 debris larger than five centimeters in diameter were detected with approximately half of this debris being in orbits with likely lifetimes of many years (Senechal, Thierry). Table 1 on the next page shows cataloged debris collected by the SSN of the ten worst satellite breakups, as of March 2012.

Common Name	Owner	International Designator	Cataloged Debris*	Debris in Orbit*	Year of Breakup	Altitude of Breakup	Cause of Breakup
Femgyun-1C	China	199-025A	3218	2989	2007	850 km	International Collision
Cosmos 2251	Russia	1993-036A	1559	1371	2009	790 km	Accidental Collision
STEP 2 Rocket Body	USA	1994-029B	710	58	1996	625 km	Accidental Explosion
Iridium 33	USA	1997-015C	567	487	2009	790 km	Accidental Collision
Cosmos 2421	Russia	2006-025A	509	0	2008	410 km	Unknown
SPOT 1 Rocket Body	France	1986-091C	492	32	1986	805 km	Accidental Explosion
OV 2-1 / LCS 2 Rocket Body	USA	1965-082DM	473	35	1965	740 km	Accidental Explosion

Nimbus 4 Rocket Body	USA	1970-025C	375	245	1970	1075 km	Accidental Explosion
TES Rocket Body	India	2001-049D	370	111	2001	670 km	Accidental Explosion
CBERS 1 Rocket Body	China	1999-057C	343	178	2000	740 km	Accidental Explosion
	*As of March 2012		Total: 8616	Total: 5506			

Table 1: Ten worst cataloged satellite breakups [NASA] (reproduced) (APPEL)

1.2.2 International Policies

Numerous space-faring nations began to realize the issues posed by space debris and have implemented various measures to alleviate this debris. Today, there is a wide interest in the problem from the scientific community and several organizations have been set up to promote various guidelines for objects launched into space.

Space debris activities started to display momentum around the 1980s with initial interest by the United States. The U.S. and NASA took a step forward and established the NASA Orbital Debris Program Office located at Johnson Space Center (JSC) in Houston, TX, in 1979, which dedicated itself to be the international lead for measurements and mitigation measures (Astromaterials Research & Exploration Science: Orbital Debris Program Office). The program is closely aligned with the DOD in many areas involving SSA, works in different ways to support the goal of continued space exploration with minimal orbital debris impact (APPEL). President Ronald Reagan’s 1988 National Space Policy of the United States of America rose national consciousness to the space debris issue.

In 1995, NASA was the first space agency in the world to issue a comprehensive set of orbital debris mitigation guidelines. Two years later, the U.S. Government developed a set of Orbital Debris Mitigation Standard Practices based on the NASA guidelines, which was later adopted in 2001 (U.S. Government Orbital Debris Mitigation Standard Practices). The U.S. Government Orbital Debris Mitigation Standard Practices addresses four key areas: control of debris during normal operations, minimization of debris generated by accidental explosions, mission planning to lower risk of debris generation, and post-mission disposal of spacecraft/structure (APPEL). The National Space Policy of the United States of America directs agencies and departments to implement U.S. Government Orbital Debris Mitigation Standard Practices. The U.S. has also endorsed the United Nations’ Space Debris Mitigation Guidelines (APPEL).

The United States is not the only country that has taken steps forward on the matter of space debris; other countries and organizations have followed suit with their own orbital debris mitigation guidelines. In 1993, the Inter-Agency Space Debris Coordination Committee (IADC) was created at the 7th NASA/European Space Agency (ESA) coordination meeting (Senechal, Thierry). The IADC is one of the world’s leading technical organizations primarily focused on all matters related to orbital debris. Today, the IADC is an international forum of governmental bodies for the coordination of activities related to the issues of man-made and natural debris in space (Senechal, Thierry). The committee meets annually and consists of four working groups: debris management, modeling techniques, impact protection, and debris mitigation. In 2002, after a multi-year effort, the IADC, consisting of representatives from Canada, China, France, Germany, India, Italy, Japan, Russia, Ukraine, the United Kingdom, the United States, and the ESA adopted a consensus set of guidelines designed to mitigate the growth of the orbital debris population (APPEL).

The ESA developed their Space Debris Working Group in 1986 and in February 1999, they issued a Space Debris Mitigation Handbook, following the publication of NASA mitigation guidelines for orbital debris. Followed by a Space Debris Safety and Mitigation Standard in 2000, the ESA now conducts space debris research at the European Space Research and Technology Centre (ESTEC) (APPEL).

In 1994, the subject of orbital debris was first introduced to the agenda for the Scientific and Technical Subcommittee (STSC) of the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS). In February 2007, UNCOPUOS STSC completed a multi-year work plan with the adoption of a consensus set of space debris mitigation guidelines very similar to the IADC guidelines. The guidelines were then accepted by the COPUOS in June 2007 and endorsed by the United Nations in January 2008 (European Conference on Space Debris Risks and Mitigations).

The Federal Space Agency of Russia relies heavily on the UNCOPUOS STSC for internationally approved measures, and also produced their own General Requirements to Spacecraft and Orbital Stages on Space Debris Mitigation in 2000.

Below, Table 2 demonstrates a timeline of U.S. and International orbital debris mitigation guideline developments.

1979	NASA Orbital Debris Program Office created at Johnson Space Center
1986	ESA developed Space Debris Working Group
1988	Ronald Reagan’s National Space Policy brought attention to space debris issue
1993	IADC was established
1994	Orbital debris was first introduced at STSC of UNCOPUOS
1995	NASA issued Orbital Debris Mitigation Guidelines
1997	U.S. Government developed Orbital Debris Mitigation Standard Practices
1999	ESA issued Space Debris Mitigation Handbook
2000	ESA published Space Debris Safety and Mitigation Standard
2000	Federal Space Agency of Russia produced General Requirements to Spacecraft and Orbital Stages on Space Debris Mitigation
2001	U.S. Government Orbital Debris Mitigation Standard Practices was adopted, put in effect
2002	IADC released first consensus of International Guidelines: the IADC Space Debris Mitigation Guidelines
2007 (Feb)	UNCOPUOS STSC adopted consensus of Space Debris Guidelines similar to IADC Guidelines
2007 (June)	COPUOS accepted Space Debris Guidelines
2008 (Jan)	UN endorsed Space Debris Guidelines

Table 2: History of U.S. and International orbital debris mitigation guideline developments (Shellabarger)

World geopolitics has dramatically changed since the 1960’s race to the moon. At the time, the US and the Soviet Union competed with one another, both on Earth and in space. Today, the two nations are partnering on common projects along with a number of other nations. The International Space Station (ISS) is the most convincing example of international cooperation, not only between two space leaders, but also involving fourteen other nations: Belgium, Brazil, Canada, Denmark, France, Germany, Japan, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and the United Kingdom. As stated by Frost & Sullivan, (Senechal, Thierry) "international cooperation has greatly enhanced national efforts in space-based science, observation, telecommunications, and manned exploration. Space research and development shifted from national confidential to government and industry collaborative programs to international cooperative projects." Because of this, the U.S. and other spacefaring nations and organizations have taken steps to monitor the space environment and manage data and information on debris, minimize its generation, and implement measures to survive contact with debris in space. As a result of this international cooperation, individual efforts in debris research are enhanced through technical coordination and consensus, and are leading to a better understanding of debris and its implications for the utilization of outer space (Interagency Report on Orbital Debris 1995).

Chapter 2: Review of Previous Work/Studies

Controlling the amount of space debris has become a well-researched and in-depth topic. Over the last couple of decades, countries' governments, space industries, companies, and universities have completed research, as well as produced prototypes, on how to eliminate the amount of space debris in Earth's orbit. This following chapter will discuss the previous work of predicting future debris and the current techniques and studies on the topic of space debris.

2.1 Predicting Future Debris

In 1978, Donald J. Kessler, a NASA scientist, proposed a nightmare scenario, which came to be known as the “Kessler Syndrome.” He stated that if the growth of orbital debris in LEO continued unchecked, the density of objects could become so great that the objects would increasingly collide, each collision generating more debris, which would cause space exploration and satellite use to become more hazardous (APPEL).

While Kessler’s prediction might have seemed negative, by 2006 scientists were forecasting a similar situation. In their article, “Risk in Space from Orbiting Debris,” Jer-Chyi Liou and Nicholas L. Johnson stated that even if no new launches were conducted after 2006, “The current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future.” In Figure 3 below, you can see that although operational debris and debris from inoperative objects was expected to start declining by the late 2000s, the authors proposed that debris arising from collisions would increase dramatically and consistently in the years to come (APPEL).

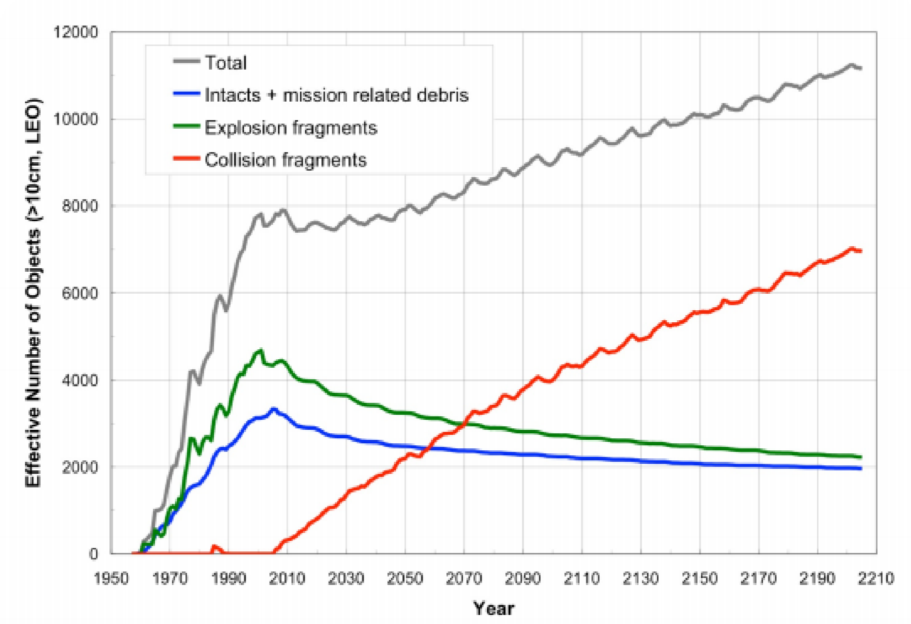

Figure 3: Projected instability of the LEO population [NASA] (APPEL)

By 2009, the scenario looked even worse. The intentional destruction of the Chinese weather satellite, Fengyun-1C in 2007, along with the accidental collision between Iridium 33 and Cosmos 2251 in 2009, greatly increased the amount of debris in LEO. As a result, the likelihood that active spacecraft would collide with orbital debris increased significantly. Figure 4 shows that projection with the uncertainty of 1- sigma sign (APPEL).

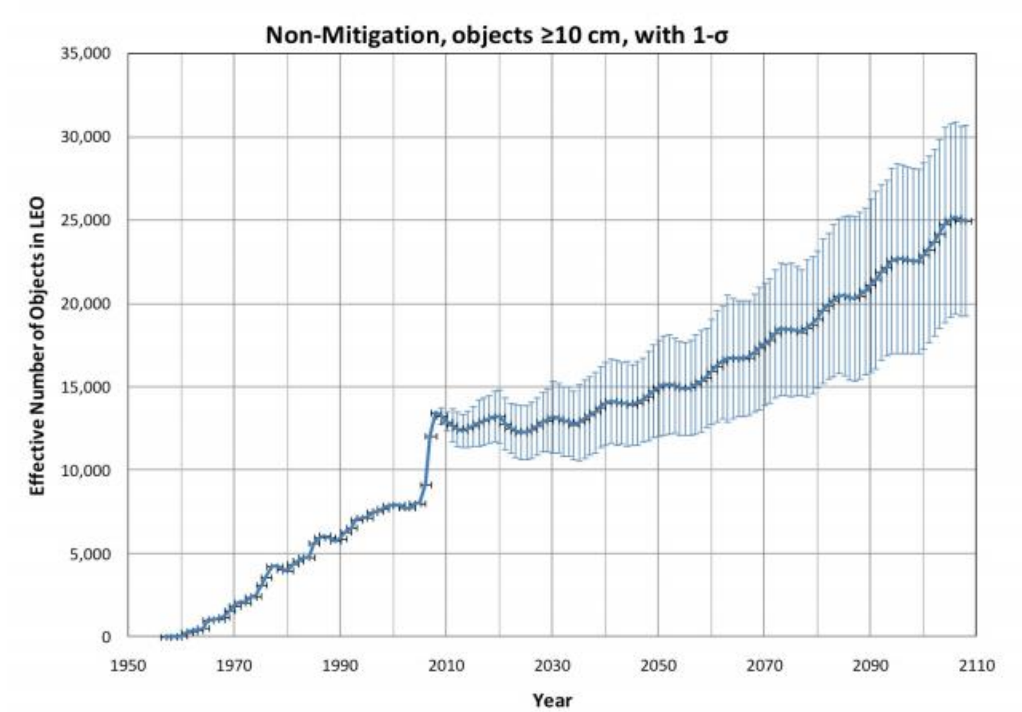

Figure 4: 2009 Projection of orbital debris in LEO [NASA] (APPEL)

2.2 Current Techniques

Organizations that function in space around the world have come to grasp that if the volume of orbital debris in LEO and GEO is not truncated, it could limit or possibly eliminate space exploration altogether. Options are accessible to control, limit, or reduce the growth of orbital debris. However, none of them can significantly alter the current debris environment; they can impact the future environment. Some of the previous and current techniques to control the amount of space debris, whether it be inoperative objects, operational debris, or fragmentation debris, include the following: removal strategies, avoidance tactics, and mitigation systems.

2.2.1 Removal Strategies

One of the most common researched and studied areas on orbital debris is removal strategies. Removal strategies consist of ways to help remove the debris that is already in orbit.

Tools such as tethers, lasers, space tugs, and a Space Debris Elimination (SpaDE) system have been explored by NASA and other civil companies for their potential to de-orbit debris. This process would cause orbital debris to re-enter Earth's atmosphere quicker than it normally would with the "25-year rule" mandating that debris must be removed from LEO within 25 years of the mission termination.

Some of the tethers that NASA has been researching are complex and costly to use, but would remove a large-mass piece of orbital debris are known as conductive and momentum tethers. Conductive tethers, also known as electrodynamic tethers, is a long conducting wire that generates electric potential by its motion through the Earth's magnetic field. This type of tether could be attached to the targeted piece of debris, and the current generated by the tether would produce a charge that de-orbits the object, causing it to re-enter Earth's atmosphere more quickly that it would if it stayed in orbit (APPEL). A momentum tether is a non-conductive tether that would attach to a piece of orbital debris. The tether is first swung back and forth to generate momentum, then it would be severed. Once the tether is cut, the resulting momentum swings the object out of orbit and into Earth's atmosphere (APPEL).

Figure 5: Conductive Tether [NASA] (APPEL)

The force created by current flowing through a conductive tether can slow a spacecraft down and take energy out of its orbit. The spacecraft would deploy the tether, the object would slow down, and eventually re-enter Earth's atmosphere where it will burn up.

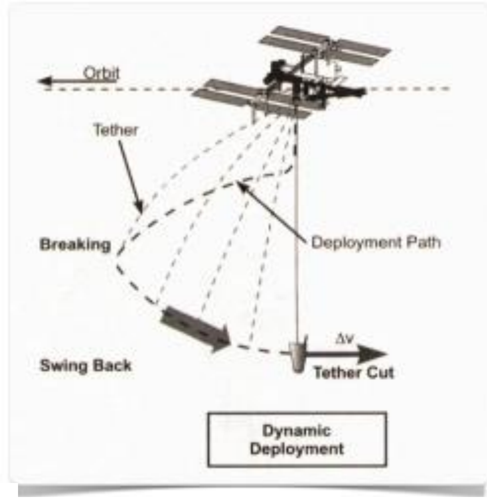

Figure 6: Momentum Tether [NASA] (APPEL)

A momentum tether would function on the principle of dynamic release to de-orbit large pieces of orbital debris.

Laser technologies could potentially remove a large quantity of small debris. The concept is to lock onto the orbital debris using ground, air, or space-based lasers, then vaporize some part of the debris, creating a thrust that causes the debris to alter its orbit. This would lessen the lifetime of the debris. However, such an approach raises issues of arms control (for ground- and air-based lasers) and U.N. treaty violations (for space-based lasers). In addition, it would be an enormous undertaking, as the number of hazardous small debris is quite large (APPEL).

A space tug is actually a spacecraft that would be used to move multiple pieces of debris to disposal orbits in GEO. In this scenario, a tether is attached to one object; after a link is achieved, the object is transferred to disposal orbit, and the process is repeated with a second piece of orbital debris. This approach could be effective for disposing of objects in GEO, and its multi-target capability makes it attractive. Again, however, it is unproven, and would be complex and costly to use (APPEL).

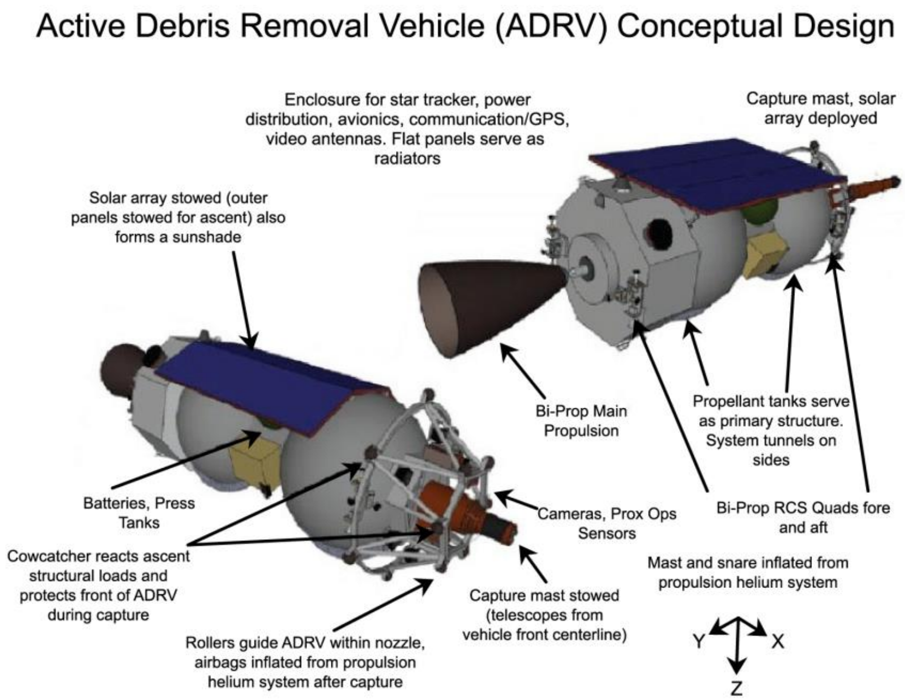

Figure 7: Space Tugs [NASA] (APPEL)

Space tugs are spacecraft that would be used to remove large objects from GEO. These tugs are particularly attractive due to their multi-target capability. The above figure depicts an ADRV conceptual design.

Current strategies emphasize debris mitigation, as there is no practical method for debris removal. NASA, Raytheon BBN Technologies (BBN) and the University of Michigan have studied the Space Debris Elimination (SpaDE) system to remove debris from orbit. SpaDE focuses the use of pulses of atmospheric gases to accelerate the rate of decay on debris by creating a temporary drag that causes the debris to re-enter the atmosphere sooner than would naturally occur. The pulses themselves soon fall back into the atmosphere, leaving no residual trace in orbit to interfere with LEO satellites. Air pulse braking can be effective on debris ranging in size from paint flakes to spent booster casings. In contrast to other proposed methods, SpaDE is failsafe, in that it places no solid material in orbit where a malfunction could create new debris. SpaDE should provide a lower cost alternative to orbiting a removal system. The SpaDE system window of opportunity is measured in tens of seconds and kilometers, meaning there is a wide range of possible starting conditions that will yield favorable results (Gregory, Daniel, et al).

Figure 8: Space Debris Elimination (SpaDE) System overview [NASA] (Gregory, Daniel, et al)

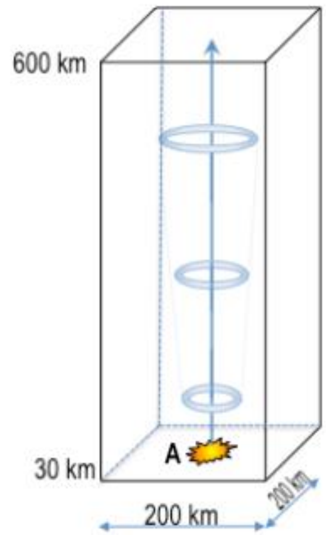

Figure 9: SpaDE launches air pulses from Point A into LEO [NASA] (Gregory, Daniel, et al)

SpaDE will use a device mounted on an airborne platform (e.g., a high-altitude balloon) to propel pulses of atmospheric gas into space that will that maintain their cohesion during transit to orbital altitudes. The operational altitude of the platform would be between twenty-five and thirty-five kilometers, to minimize drag effects from the dense lower atmosphere. If the SpaDE project continues its research and risk reduction analysis, a prototype deployment of a SpaDE system may occur in the future (Gregory, Daniel, et al).

2.2.2 Avoidance Tactics

Another commonly researched and studied area on orbital debris is avoidance tactics that include ways to help reduce the collision probability impact for debris already in orbit. Collisions, both accidental and intentional, are responsible for much of the debris in Earth's orbit. As for the ISS, NASA has a set of long-standing guidelines that are used to assess whether the threat of such a close pass of orbital debris is sufficient to warrant evasive action or other precautions to ensure the safety of the crew on-board (Garcia, Mark).

These guidelines essentially draw an imaginary box, known as the "pizza box" because of its flat, rectangular shape, around the space vehicle. This box is about a mile deep by thirty miles across by thirty miles long (1.5 x 50 x 50 kilometers), with the vehicle in the center. When predictions indicate that the debris will pass close enough for concern and the quality of the tracking data is deemed sufficiently accurate, Mission Control centers in Houston and Moscow work together to develop a prudent course of action. Sometimes these encounters are known well in advance and there is time to move the station slightly, known as a "debris avoidance maneuver" to keep the debris outside of the box (Garcia, Mark).

Debris avoidance maneuvers are planned when the probability of collision from a conjunction reaches limits set in the ISS flight rules. If the probability of collision is greater than 1 in 100,000, a maneuver will be conducted if it will not result in significant impact to mission objectives. If it is greater than 1 in 10,000, a maneuver will be conducted unless it will result in additional risk to the crew. These maneuvers are usually small and occur from one to several hours before the time of the conjunction. Such maneuvers with the ISS require about thirty hours to plan and execute mainly due to the need to use the station's Russian thrusters, or the propulsion systems on one of the docked Russian or European spacecraft (Garcia, Mark).

Other times, the tracking data isn't precise enough to warrant such a maneuver or the close pass isn't identified in time to make the maneuver. In those cases, the control centers may agree that the best course of action is to move the crew into the Soyuz spacecraft that is used to transport humans to and from the station. This allows enough time to isolate those spaceships from the station by closing hatches in the event of a damaging collision. The crew would be able to leave the station if the collision caused a loss of pressure in the life-supporting module or damaged critical components. The Soyuz spacecraft acts as lifeboats for crew members in the event of an emergency (Garcia, Mark).

As for non-NASA operational satellites in LEO or GEO, the SSN will track orbital debris and warn the operators of each satellite the risk of collision between their satellite and the orbital debris. From there, satellite operators can usually control, if there is enough warning time, whether or not they will use their spacecraft propulsion to alter their orbital altitude in order to avoid collision.

For satellites in GEO, the typical way to reduce the number of inoperative objects is to use a spacecraft's propulsion and the rest of the fuel to venture out into a "graveyard orbit," seen in Figure 10 (Garcia, Mark). This orbit is typically three-hundred kilometers above GEO, and no longer poses a risk to those operational satellites in GEO.

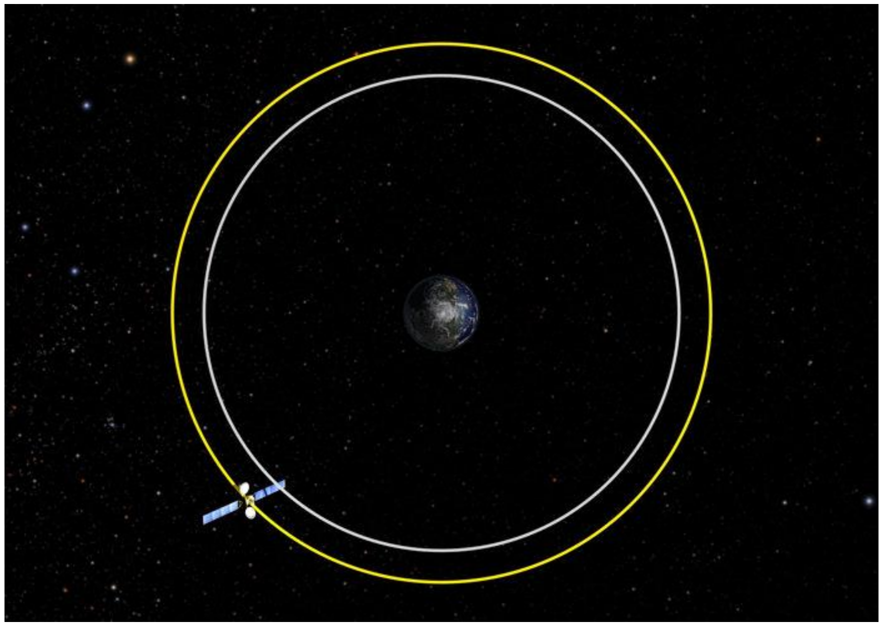

Figure 10: Graveyard orbit (yellow) for inoperative objects from GEO (Garcia, Mark)

2.2.3 Mitigation Systems

The last reoccurring area that is researched for space debris clean-up is the act of mitigation systems. Mitigation systems are engineered to help reduce the current growth of space debris with new techniques for future missions. Even before governments began to develop orbital debris-related policies and guidelines, launch vehicle developers became aware of the risks associated with orbital debris and began to explore ways to mitigate this hazard. One of the earliest procedures U.S. vehicle manufacturers adopted was the passivation, or depletion of on-board energy sources, of upper stages to prevent them from exploding and fragmenting.

Passivation includes the burning or venting of residual propellants, the release of pressurants, the discharge of batteries, and the spinning down of momentum wheels and devices with rotational energy. It is believed that more than 80% of all upper stage explosions could have been prevented by passivation. The passivation of U.S. launch vehicles started in the early 1960s, when Thor-Ablestar upper stages vented leftover fuels. Over time, as upper stages of U.S. and non-U.S. upper stages experienced explosions and fragmented, passivation caught on among the world's launch vehicle developers. By the 1980s and 1990s, passivation became a standard procedure on Delta, Pegasus, Atlas, and Titan orbital stages. Foreign upper stages, such as those of the Ariane, Long March, and Zenit, now also employ passivation measures. The cost of passivation can be relatively small if it is planned in a vehicle's design phase (Launch Activity and Orbital Debris Mitigation).

Until 2007, launch vehicle upper stage explosions were the single greatest contributor to the creation of orbital debris. Most of the explosions were accidental and occurred after successful deployment of a satellite, generally within twenty-four hours to two decades after launch. Typically, the explosions were caused by leftover propellant that ignited long after launch. The results of such explosions ranged from a few pieces of debris to several hundred large fragments accompanied by many more small pieces. Ejection velocities ranged from less than one meter per second to hundreds of meters per second. Two hundred such events have been identified. Today, passivation of the upper stages following mission completion is required to prevent explosions. This approach has been highly successful (APPEL).

SpaceX was founded by CEO and Lead Designer Elon Musk in 2002 and has gained worldwide attention for a series of historic milestones. It is the only private company capable of returning a spacecraft from LEO, which it first accomplished in 2010. SpaceX has been working to make its rockets partially reusable since as early as 2011. The company's strategy has been to land its rockets after launch in an effort to fly them again and again. Although, they don't save the entire Falcon 9 rocket after each launch. They save the first stage — the fourteen story core of the Falcon 9 that contains the main engines and most of the fuel needed for launch. About a few minutes after takeoff, the first stage separates from the top of the rocket and makes a controlled descent back to Earth — either landing on solid ground or on one of the company's autonomous drone ships in the ocean (Grush, Loren).

The company made history again in 2012 when its Dragon spacecraft became the first commercial spacecraft to deliver cargo to and from the International Space Station. SpaceX successfully achieved the historic first re-flight of an orbital class rocket in 2017, and the company now regularly launches flight-proven rockets. Although Musk believes that using reusable rockets will "substantially reduce the cost of space access," reusable rockets will also help with decreasing the amount of operational debris in LEO (SPACE EXPLORATION TECHNOLOGIES CORP.).

Chapter 3: Trade study

Space-faring nations, along with the United States' DOD and NASA, have been designing new techniques and establishing more policies for LEO, GEO, and space activities in the future. Along with the research conducted pertaining to space debris, a new subsystem for future satellites has been researched and presented to prevent the amount of debris in space. The following sections will cover the subsystem.

3.1 Mitigation for Future Endeavors

Controlling the growth of the orbital debris population is a high priority for NASA, the United States, and the major space-faring nations of the world to preserve near-Earth space for future generations. Mitigation measures can take the form of curtailing or preventing the creation of new debris, designing satellites to withstand impacts by small debris, and implementing operational procedures such as using orbital regimes with less debris, adopting specific spacecraft attitudes, and even maneuvering to avoid collisions with debris (Space Surveillance).

Another way to mitigate space debris would be to design and produce a new subsystem to place on satellites for future launches. Although the following subsystem will not solve the ever-evolving debris that is already in orbit, it can help delay the space debris problem that poses a threat to space missions.

3.2 Subsystem Design

During research, an idea of producing retrograde thrusters came to light. This subsystem would use thrusters in the opposite direction of the propulsion system. This thrust in the opposite direction makes resistance to the satellite's velocity, and thus decreases its speed. Slowing down the satellite would potentially lower the orbital altitude 200-500 meters and allow the satellite to decay naturally due to Earth's gravitational field. This mechanism would not allow the satellite to enter Earth's atmosphere right away; but it would allow the satellite to enter the atmosphere at a much quicker rate than the 25-year rule. Also, having the satellite at a lower orbit would reduce the amount of debris in LEO, ultimately reducing the probability of collisions for future debris to form.

The following subsystem was displayed on a 2U CubeSat, with two solar panels, and a dipole antenna. Although the subsystem is shown on a 2U CubeSat, the thrusters could be modified in size and integrated onto smaller/larger satellites. This computer aided drawing (CAD) model was designed to show the overall satellite design, with little detail pertaining to the inside and body of the spacecraft. Figures 11, 12, and 13 below will illustrate the look of the satellite while it is in orbit, along with views emphasizing the front and rear ends with the retrograde thrusters and propulsion system.

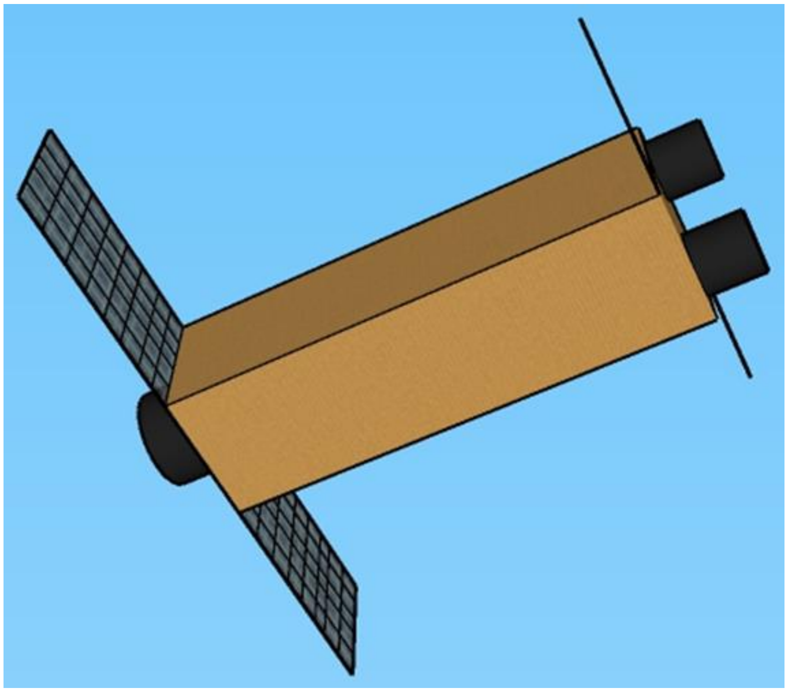

Figure 11: 2U CubeSat displaying retrograde thrusters (Shellabarger)

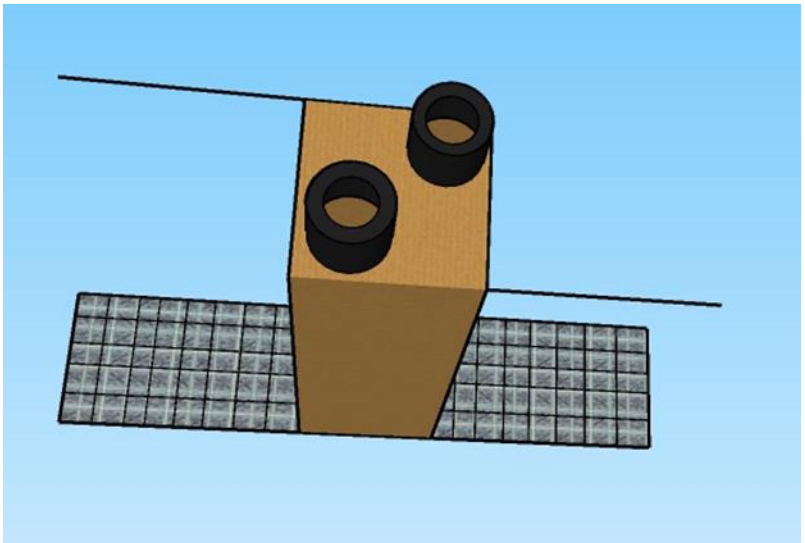

Figure 12: Front-view of CubeSat, emphasizing two retrograde thrusters (Shellabarger)

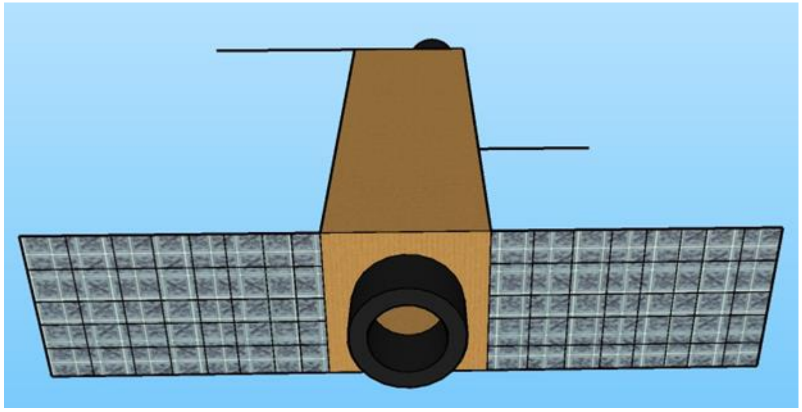

Figure 13: Rear-view of CubeSat, emphasizing the propulsion system (Shellabarger)

Understanding how the retrograde thrusters work is the main element when designing the satellite. In general, retro means backwards or behind. Retro-burning means firing in the opposite direction from the original means of propulsion. The propulsion system will fire occasionally to keep the satellite moving at the intended velocity to stay in its orbit, which can be seen from Figure 14. The thrust in the opposite direction from the retrograde thrusters makes resistance to the satellite's movement and velocity, thus reducing its speed and slowing the satellite down, shown in Figure 15. Figure 16 displays the new speed of the satellite; the old speed minus the retro burning of the thrusters.

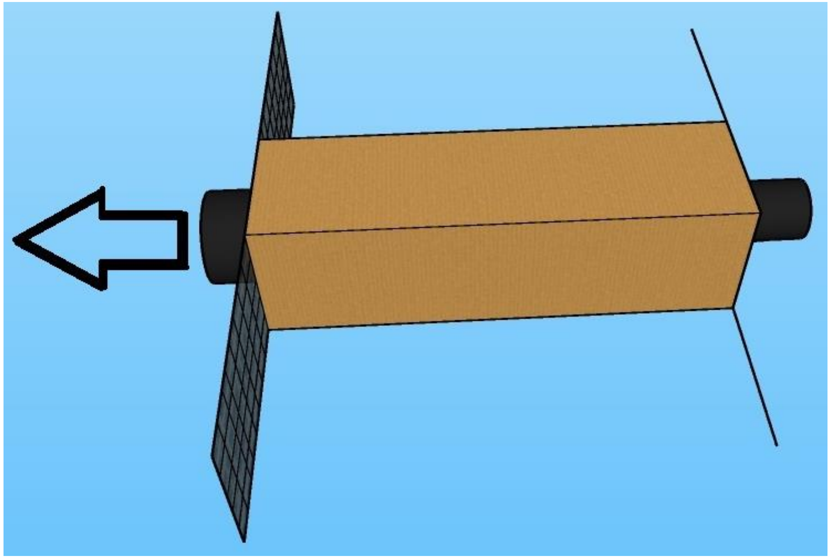

Figure 14: Propulsion system firing to keep the satellite at its intended velocity to stay in orbit (Shellabarger)

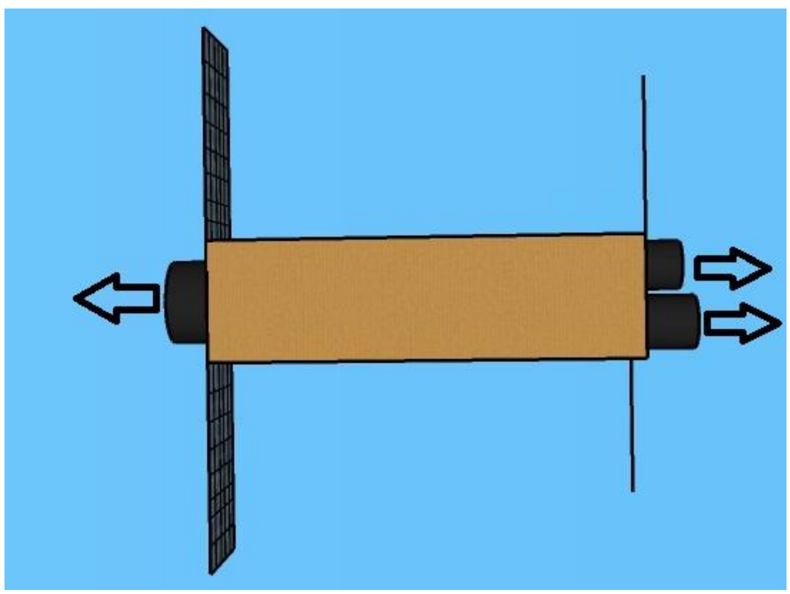

Figure 15: Retrograde thrusters at the front of the satellite fire in the opposite direction from the propulsion, creating resistance and reducing the speed of the satellite (Shellabarger)

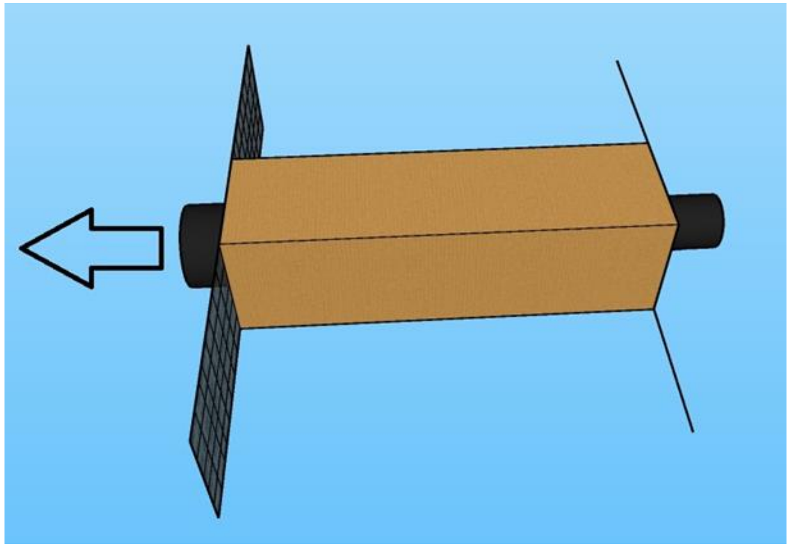

Figure 16: The new speed of the satellite; the old speed minus the retro-burning of the thrusters (Shellabarger)

Creating resistance to reduce the speed of a satellite would ultimately change and lower the satellite's orbital altitude. This reduction in altitude would place the satellite closer to the Earth's atmosphere, increasing the amount of gravitational pull and allow the satellite to decay naturally by entering the Earth's atmosphere and burn-up upon re-entry. The retrograde thrusters would be very beneficial in the production of future satellites. This subsystem would potentially mitigate the amount of future space debris (pending collisions and causing more fragmentation debris) by reducing the amount of time an inoperative object would remain in space. Although the 25-year rule is in place, that is essentially too long for inoperative objects to stay in orbit and pollute the orbital environment around the Earth. In order to use the retrograde thrusters effectively, the satellite's ground station would determine when the satellite is almost at the EOL cycle, and use the remaining amount of fuel and power to activate the thrusters. This operation would ignite the thrusters, reduce the speed, and lower the orbital altitude to begin the descent into the atmosphere to disintegrate.

3.3 Next Steps of Trade Study

With the concept and overall satellite design constructed, the next step of the process would be to engineer the retrograde thrusters and conduct testing on the subsystem itself, then integrated onto a satellite. Unfortunately, for this thesis, the time and resources are not available to take those next steps and produce thrusters or a satellite with retrograde thrusters. If the resources, time, and experience for producing retrograde thrusters were available, an engineering model would be produced for testing and possibly integrated with a cubesat for testing.

Chapter 4: Effectiveness of Previous Studies and Trade Study

From experience, some ideas, prototypes, and subsystems tend to be more effective than others. What makes one idea better than another? Does one require more research, more development, or more testing than another? The following section will discuss the effectiveness of the previous studies and research, compare the current trade study to those standards, and also mention some aspirations for the effectiveness of future studies and research.

4.1 Previous Studies' Effectiveness

Although none of the removal strategies have yet to be engineered and/or produced, a couple of the strategies appear to be more effective than the others. The two strategies that seem to be more effective are NASA's conductive tethers and the SpaDE system from NASA, BBN Technologies, and the University of Michigan. These two specific removal strategies are very different from one another, but also appear to be the most effective when removing all three kinds of debris orbiting the Earth. These two strategies would potentially be the most effective because 1) the conductive tether uses the Earth's magnetic field to generate its electric potential, attaches to an object and uses the current generated to slow down the object allowing for a quicker re-entry and 2) the SpaDE system would only submit gases into LEO to create drag and slow down the debris. The SpaDE system would not place a physical object into orbit; hence not adding to the debris problem.

Even if these strategies were to be engineered and effective, they also have some pitfalls. The tethers need a bigger physical object to be launched in order for them to work, and also have the potential to become damaged from the debris in orbit and become non-functional, causing them to become another object added to the space debris problem. The SpaDE system could be effective, but the gases sent into space could affect other operational objects in orbit that do not need to be affected by the system at that exact moment in time. The gases could affect any object that would come into contact with them and slow those objects down. Some of those objects could be newly launched satellites and not ready to deorbit and enter the Earth's atmosphere.

The effectiveness concerning the avoidance tactics has been successful thus far, although no more operations can be done to prevent collisions that isn't already being conducted. The "pizza box" around the ISS seems to be working well. This maneuver tactic keeps the ISS out of significant danger, allows the astronauts on board to remain safe from collisional damage, and preserves the ISS for future years of tests and missions. The "graveyard orbit" for satellites at GEO is a fantastic idea. This orbit gets rid of inoperative objects and reduces the amount of satellites in GEO. Reducing the volume of satellites in GEO allows for future satellites to take the orbital slot of those pushed to the graveyard orbit. The only issue one should be concerned about, would be the graveyard orbit becoming too congested. If the orbit was to become overcrowded, we would then have the same orbital debris issue at that altitude. This could potentially affect the operational satellites in GEO if this was to occur.

The mitigation systems ultimately are the most efficient and successful. Since the 1980s and 1990s when passivation became a standard procedure, the amount of upper stage explosions in space dramatically decreased. This standard is essential because it reduces the amount of fragmentation debris in LEO and in orbit. It can be a very cheap procedure if it is designed in the development stage of planning a mission. This mitigation system is the number one successful technique when it comes to reducing the amount of debris in space. The newest leading mitigation system to reduce the amount of space debris is SpaceX's partially reusable rockets- the first stage of their Falcon 9 rocket. The first stage contains the rocket's engines and most of the fuel needed for launch. Having the first stage descend back to Earth after separation from the rest of the rocket is a huge accomplishment for the space industry, and it also helps with the growing population of space debris. Before this mitigation system was produced, every part of each rocket launched into space would remain in space until it re-entered the atmosphere. Although SpaceX cannot reuse the whole rocket, having at least one of the major rocket subsystems return to Earth extremely helps the space debris problem.

Altogether, the previous studies' effectiveness appears to be pretty promising- to an extent. The avoidance tactics and the mitigation systems have been successful up until this point. The avoidance tactics have been successful for the ISS and for moving inoperative satellites to a graveyard orbit, although some satellites do not get a warning from the SSN with enough time to maneuver around the debris. The mitigation systems have been successful to this point, but not enough systems exist to help the ever-evolving space debris problem. We need systems to help mitigation of future launches. As for the current removal strategies, we are unaware of how successful or failing they could be because none have yet to be engineered and put into space to test their ability. Removal strategies are the hardest to produce because although they could help remove space debris, they could also create more debris, adding to the growing debris in space.

4.2 Current Study Effectiveness

As stated above, mitigation systems have shown to be more successful than removal strategies or avoidance tactics. For this thesis, a newly created a mitigation subsystem that could be engineered and integrated onto future satellites was proposed. This mitigation subsystem consists of applying two retrograde thrusters onto a 2U cubesat, to assist in a quicker deorbiting time, rather than relying on the 25-year rule. Unfortunately, this subsystem could not be engineered and tested to see its reliability and effectiveness. Although, it essentially could be successful in reducing the amount of space debris in the future.

This subsystem could not help with the current debris in space by removal, but it could help reduce the amount of future satellites that would remain in orbit once reaching EOL. By decreasing the number of satellites that remain in space once becoming inoperative, would thus reduce the number of objects the SSN has to track and catalogue. Also, it could reduce the probability of collisions between objects, and could ensure the orbital environment around Earth does not become even more polluted. This subsystem could also potentially be integrated onto larger/smaller satellites than a 2U cubesat. The subsystem was placed on a 2U cubesat due to personal familiarity with 2U cubesats. This subsystem would also be cheaper on smaller satellites than on larger ones due to the amount of materials that would be needed for the size of the satellite.

The only negative part about this type of mitigation subsystem would be the need to launch another object into space, much like the removal strategies mentioned above. Launching more satellites into space is bound to happen whether a subsystem like this trade study is aboard that satellite or not. Every satellite launched will increase the total volume of objects in space whether they are functional or inoperative. If such a subsystem could be verified operational and reduce the length of time an object remains in space, would be highly effective.

In order to make this trade study more effective, would be to truly understand the background of propulsion systems and retrograde thrusters and how they are engineered. If there was more time and resources to investigate these subsystems more in depth and be able to produce an engineering model for testing, this could increase the reliability on how well the subsystem could potentially work in space on future satellites.

4.3 Future Studies' Effectiveness

Unfortunately, the issue of space debris will always be a problem that the space-faring nations will have to address and attempt to solve. Space debris is a tough issue to overcome when producing systems that will be cost effective, successful, and not enhance pollution. For future studies, more engineering and testing will have to be completed, rather than just models and proposed ideas. Models and ideas are great starts but can only help the problem at hand to a certain extent. That is where engineering models and testing becomes essential. Engineering models and testing are necessary with the issue of space debris because nations do not want to cause more debris or make the situation worse.

There are countless, brilliant engineers and scientists around the world. If several countries or members of the IADC would come together and work on this issue together, producing a system or strategy that would be effective is capable. This idea could be hard to make a reality because of countries wanting to take credit of such a necessary solution to the problem of space debris. Future studies will hopefully be more effective and successful than previous studies due to the need of a solution and a desire to solve the problem.

Chapter 5: Conclusion

For sixty-one years, mankind has been venturing into space since the launch of Sputnik-1. Many nations have accomplished a lot in those sixty-one years, however, we have neglected to address a sleeping giant in the world of threats for space missions: orbital debris. It has become a vast and hazardous problem. It's time to acknowledge that while space may be infinite, Earth's orbital space is a finite resource that must be controlled properly. The orbital space around Earth has become heavily polluted, with no real solution on how to reduce the amount of debris. This leads to one of the biggest problems we face as a space-faring nation: determining how to reduce the amount of debris in space.

Currently, the Space Surveillance Network operates at twenty-five locations worldwide to track the debris as small as 5 centimeters in LEO, and one meter in GEO. There are 500,000 pieces of debris the size of a marble or larger, and many millions of pieces that are so small they cannot be tracked. Along with the SSN, international policies and individual countries' standards are endorsed and mandated with each launch. Unfortunately, the 25-year rule is the standard rule for rockets/satellites launched into space. This rule mandates that orbital debris must be removed from LEO within 25 years of operational termination. Although there are management techniques, not many operational systems actively removing, reducing, or preventing space debris exist.

As a space-faring nation, we need to reduce the volume of debris in space and stop relying too heavily on atmospheric drag to deorbit inoperative objects at the end of their design life. The main techniques that the United States and United Nations depend on are 1) removal strategies such as tethers and debris removal vehicles, 2) avoidance tactics like maneuvering around orbital debris and placing GEO satellites into a graveyard orbit and 3) mitigation systems such as passivating rocket bodies/propellants and reusable rocket bodies manufactured by SpaceX. To this day, avoidance tactics and mitigation systems are the most favorable techniques. As a nation, we need new technology to ensure spacecraft/satellites will deorbit at the end of its operational capability, which is where this thesis mitigation subsystem comes into effect.

This mitigation subsystem applies retrograde thrusters to a 2U cubesat, or even a different sized satellite, to create resistance against the satellite's propulsion in orbit. Creating resistance will reduce the speed of the satellite and lessen the orbital altitude by 200-500 meters. This allows for atmospheric drag to take effect on the satellite and re-enter the Earth's atmosphere quicker than 25 years. Even though this mitigation subsystem will not reduce the current volume of orbital debris in space, it would delay the amount of future debris if operational status was achieved. Unfortunately, there was not enough time or resources to produce this subsystem. Possibly one day in the future something to this degree will be engineered, tested, and deployed.

The effectiveness of past/current techniques depends on the solution route. The avoidance tactics and mitigation systems currently in place have been more capable than the removal strategies. The removal strategies could be effective, but are still in design phases and the cost to engineer for testing alone is extremely costly. The removal strategies and mitigation systems unfortunately still launch objects into space, which ultimately increases the total number of objects in space. Although debris would increase, it's reassuring that ideas are being researched and proposed to address the underlying giant of space debris. Hopefully the amount of dedicated research will sustain in the future and a solution(s) will be engineered and deployed to reduce the extent of space debris.

In conclusion, space-faring nations need to realize that the orbital space around Earth is not finite, and there is an ever-evolving problem of space debris that continually increases. Countries around the world need to put forth more effort in designing and fabricating products that can reduce the volume of debris in space. Whether that entails new mitigation systems on future satellites or new removal strategies that can be launched and produce positive results, something needs to be done. Current avoidance tactics are sufficiently working, along with the 25-year rule. Although that is not enough to lessen the quantity of debris in space or that will be created with new missions. Governments, agencies and engineers need to comprehend that Earth's orbital space is polluted and will become inaccessible for future endeavors unless a working system and/or solution for space debris becomes operational.

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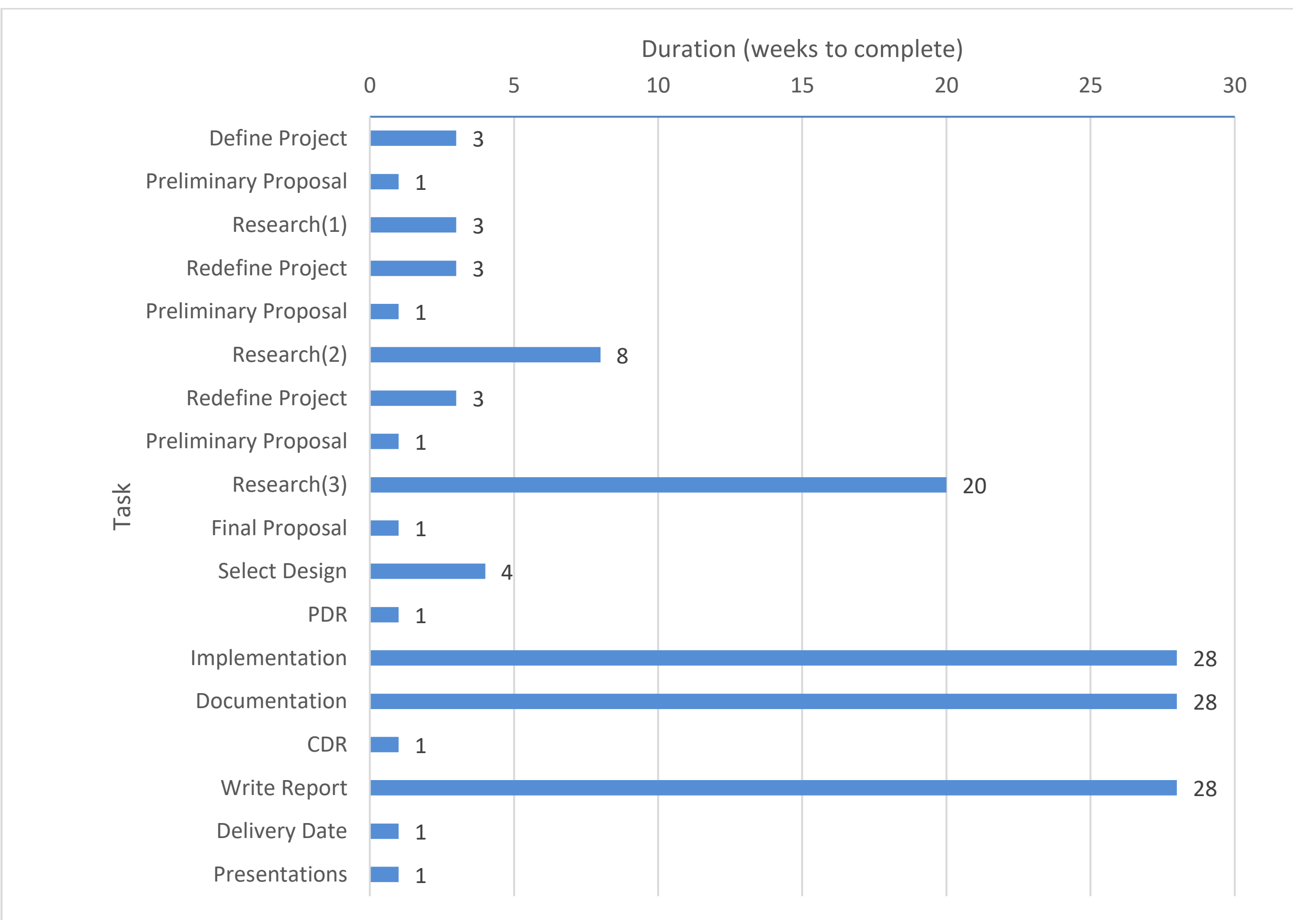
Budget

Project Budget								
Salary/Year		**Labor**		**Expenses**			**R&D**	
$ 70,000.00		33.65/hour		Materials	$ 1,000.00		Machine Time	$ -
		2080 hours		Taxes	$ 2,000.00		Research	$ 20,000.00
Mentor Salary				Insurance	$ 6,000.00		Testing	$ -
$ 5,000.00				Travel	$ 1,000.00		Repair	$ -
							Development	$ -
		$1346/week		Total	$ 10,000.00		Total	$ 20,000.00
Total Budget	$ 105,000.00							

Timeline



Resume

Brooke Shellabarger

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OBJECTIVE

Seeking a position related to small satellite systems engineering in development, environmental testing, documentation, quality assurance, analysis, and ground operations.

EDUCATION

Morehead State University – M.S. – Space Systems Engineering – 2018

Morehead State University – B.S. – Space Science – 2016

EXPERIENCE

Electronics Engineer, Wright-Patterson AFB, October 2017 – Present

- Satellite Communications (SATCOM) analyst for the PACOM Integrated C4 ISR Analysis Squadron
- Focused on learning Air Force objectives, new skills and software, and producing Department of Defense (DOD) products

High Voltage Power Supply, CXBN II, 2014-2015

- Designed and developed the layout of the high voltage power supply for CXBN II, a 2U cubesat, via Altium

Safety Engineering, Lunar IceCube, 2016-2017

- Assist the Secondary Payload Safety Engineer with documentation for Lunar IceCube, a 6U cubesat being launched on Space Launch System's EM-1
- Presented part of Lunar IceCube's Fracture Control Plan to the Fracture Control Board at Marshall Space Flight Center
- Merged several documents to form the Phase II Safety Data Package
- Prepared the End of Mission Plan for the Mission's Principle Investigator

22 GHz Water Vapor Radiometer, Senior Thesis, 2015-2016

- Researched calibration techniques, system stability, and gain sensitivity
- Tested the system's down converter and detector
- Presented to the Faculty, Staff, and Students at Morehead State University's Space Science Center

GEAR UP Kentucky Summer Academy at MSU, University Site Director, 2016-2017

- Designed a curriculum to empower and motivate first-generation high school students from Kentucky
- Educated students about components, how to breadboard and solder, collect and analyze data, and present their findings from a CricketSat

LEADERSHIP EXPERIENCE

- Graduate Assistant – Instructor (D.C. Circuits Lab) – 2016-2017

- Delta Gamma Sorority – Director of Funds – 2014-2015
- Small Satellite Conference – 2014 & 2016
- CubeSat Conference – 2015